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Dalton et al.

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(54) **GROUND FAULT DETECTION METHODS ON VARIABLE FREQUENCY DRIVE SYSTEMS**

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See application file for complete search history.

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H02H 3/17 (2006.01)
H02H 3/16 (2006.01)

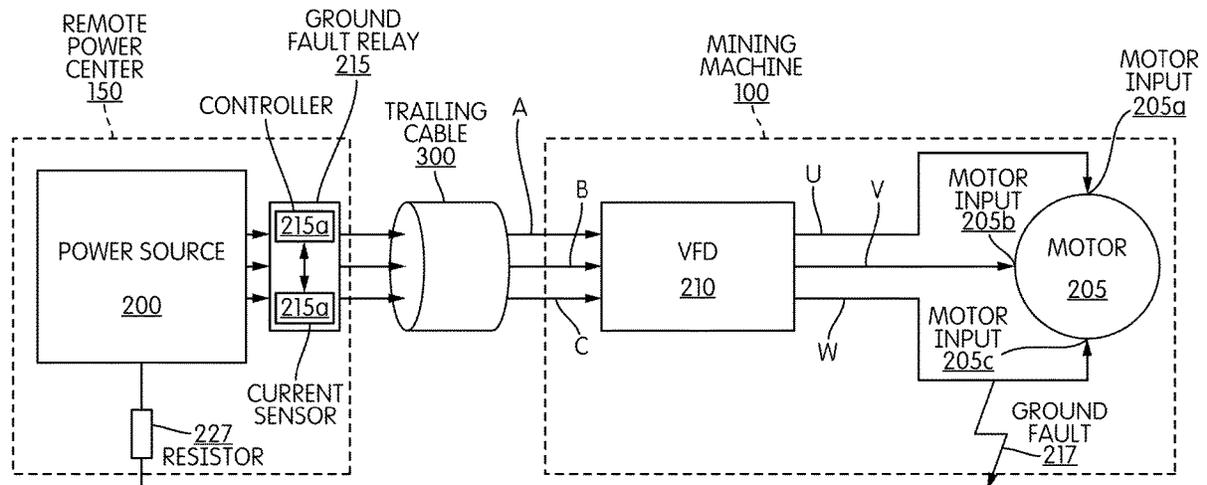
(57) **ABSTRACT**

(52) **U.S. Cl.**
 CPC **H02P 27/04** (2013.01); **H02H 3/162** (2013.01); **H02H 3/17** (2013.01); **H02H 3/165** (2013.01)

A mining machine including a motor, an adjustable speed drive providing a voltage to the motor, the voltage having an excitation component comprising a magnitude and a frequency for operating the motor at a desired speed and including an additional voltage component for use in detecting a ground fault condition, and a ground fault relay for detecting a ground fault current when the ground fault current exceeds a predetermined threshold.

(58) **Field of Classification Search**
 CPC H02H 3/162; H02H 3/17; H02H 3/165; H02P 27/04

13 Claims, 6 Drawing Sheets



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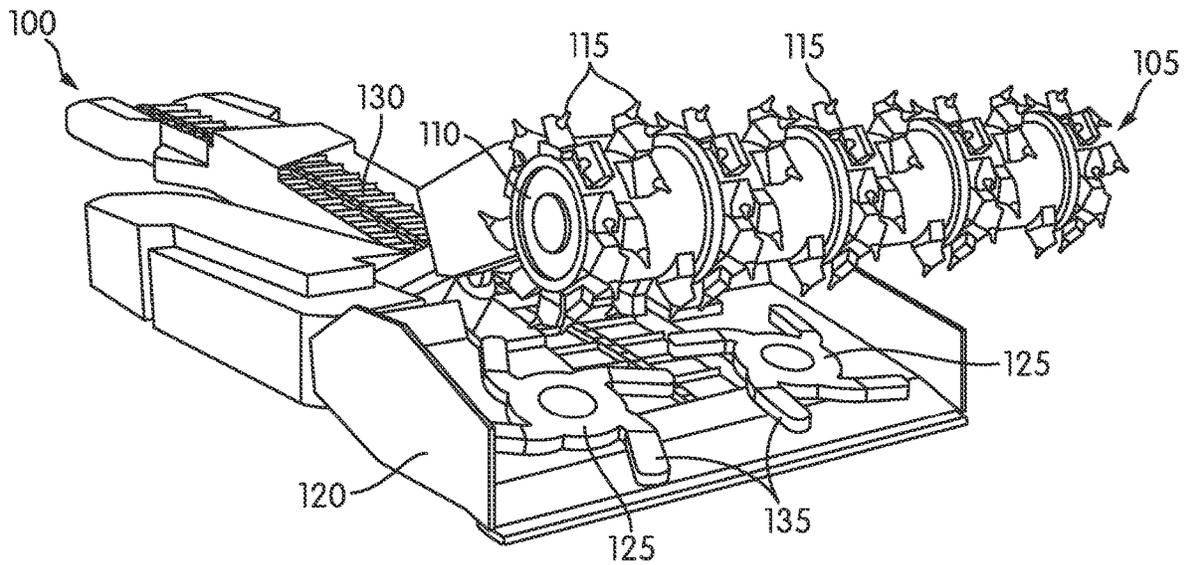


FIG. 1A

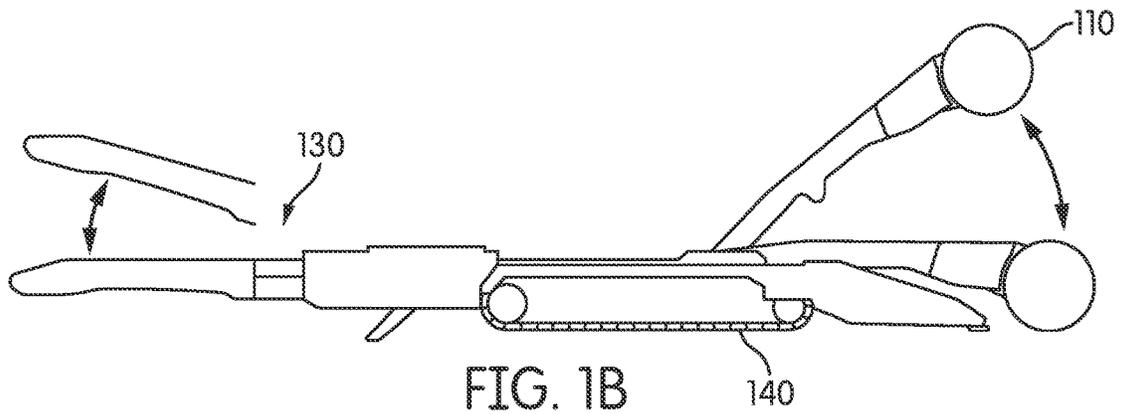


FIG. 1B

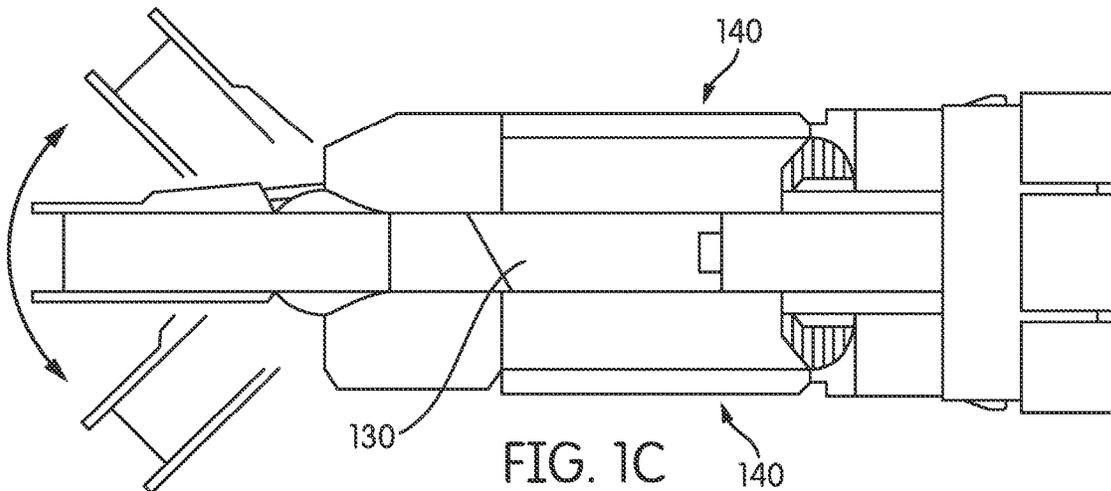


FIG. 1C

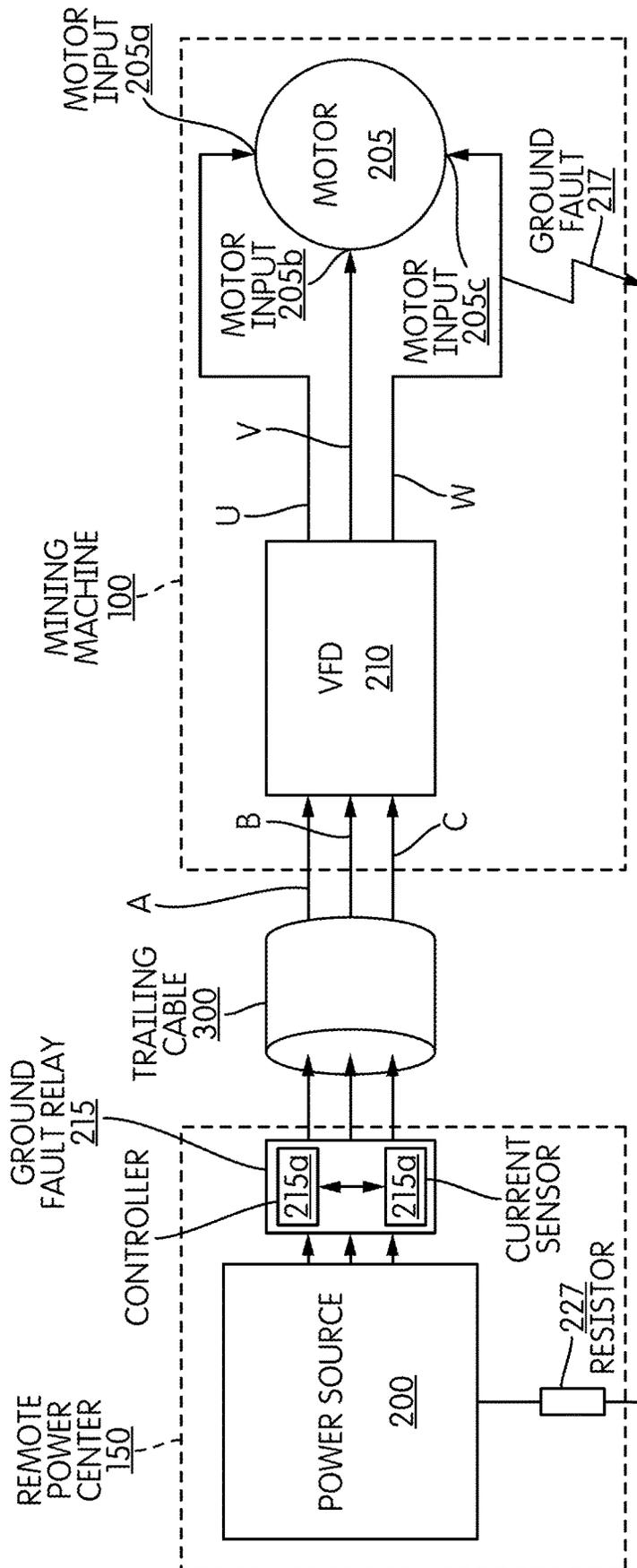


FIG. 2A

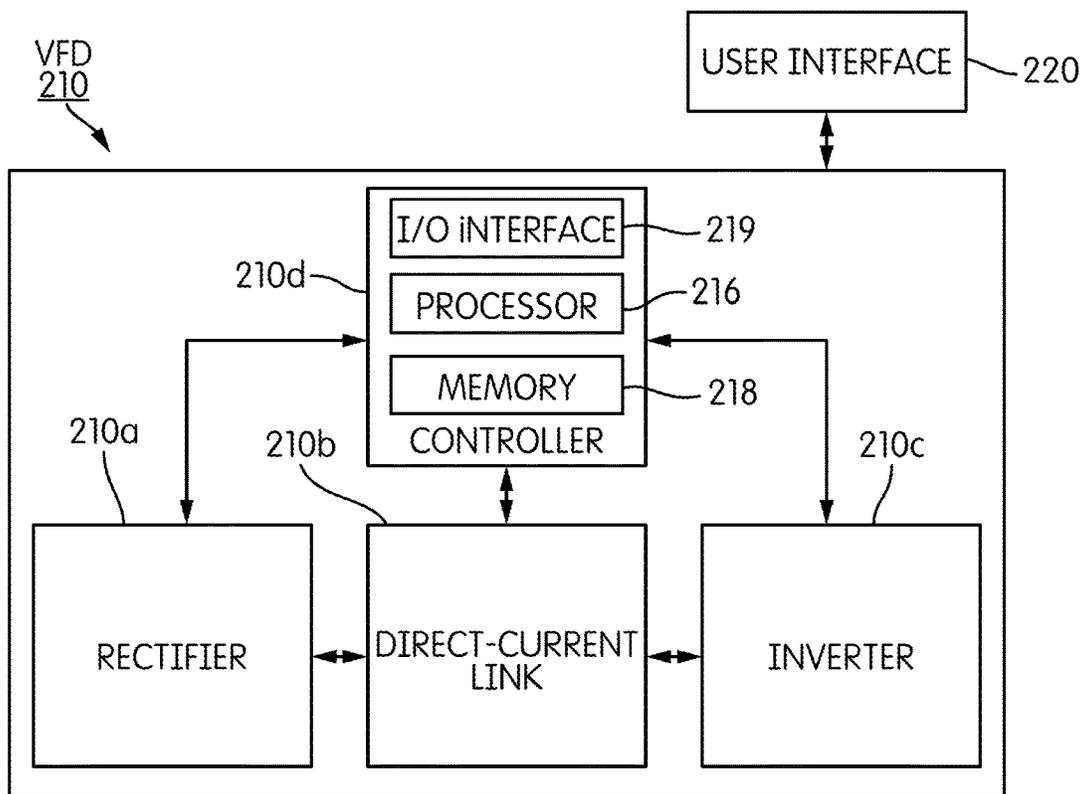


FIG. 2B

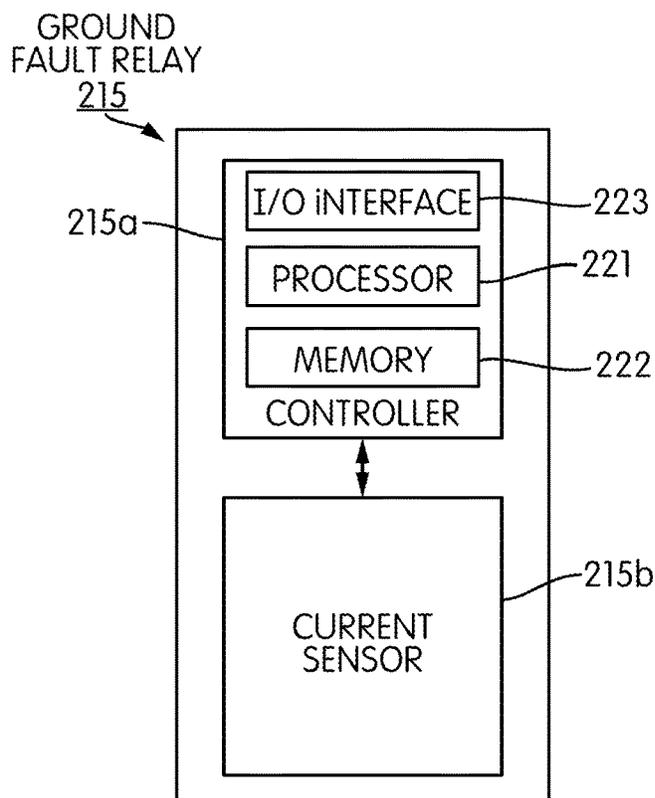


FIG. 2C

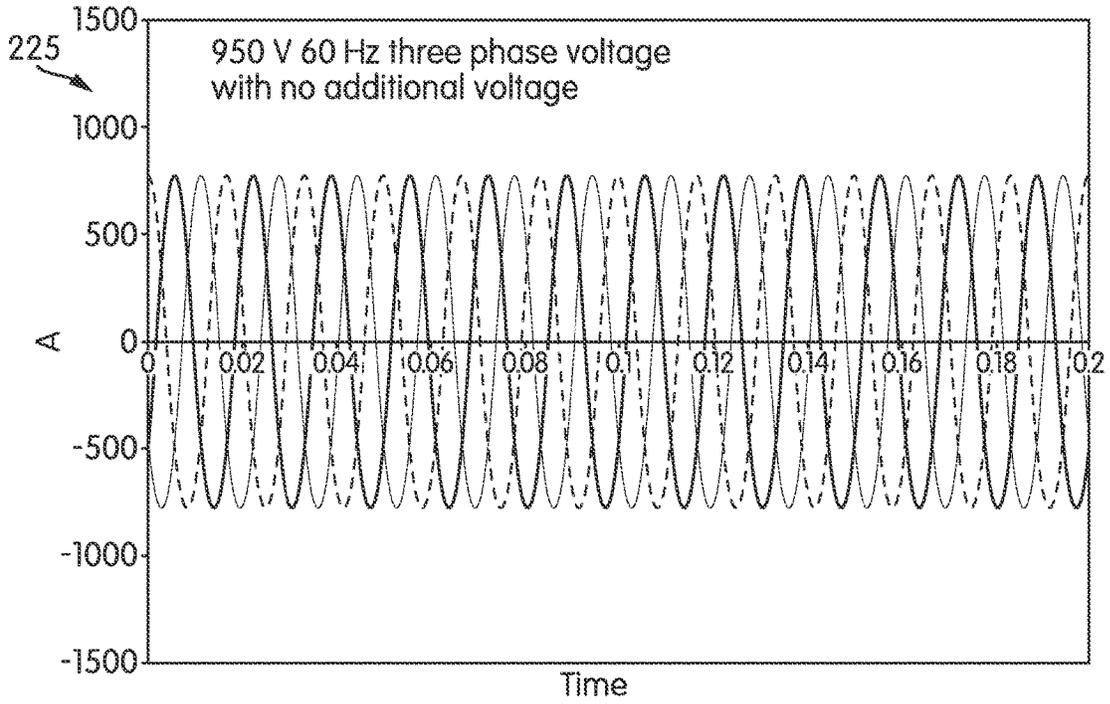


FIG. 3

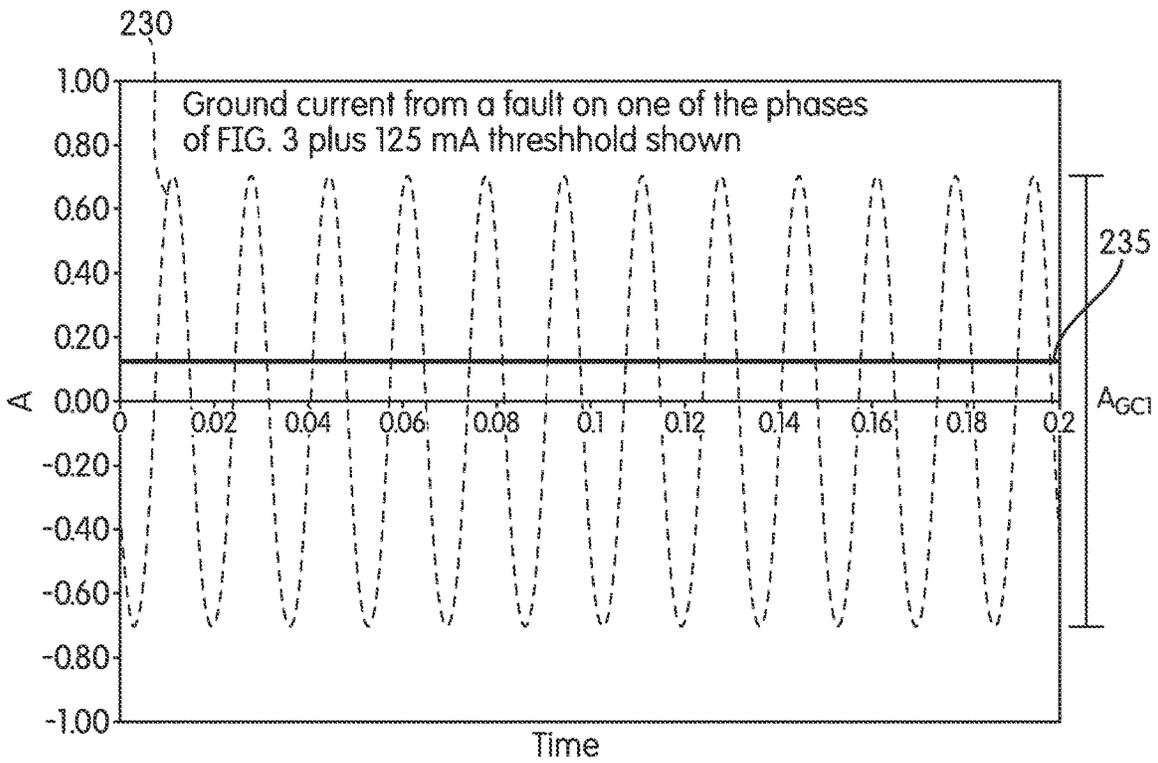


FIG. 4

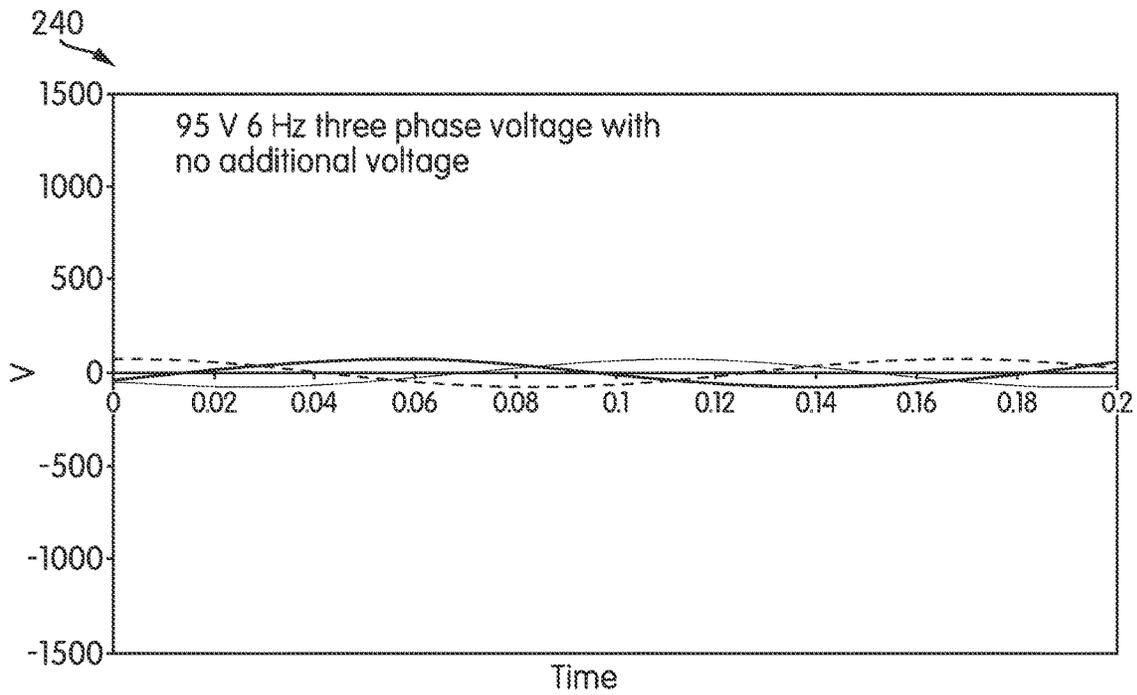


FIG. 5

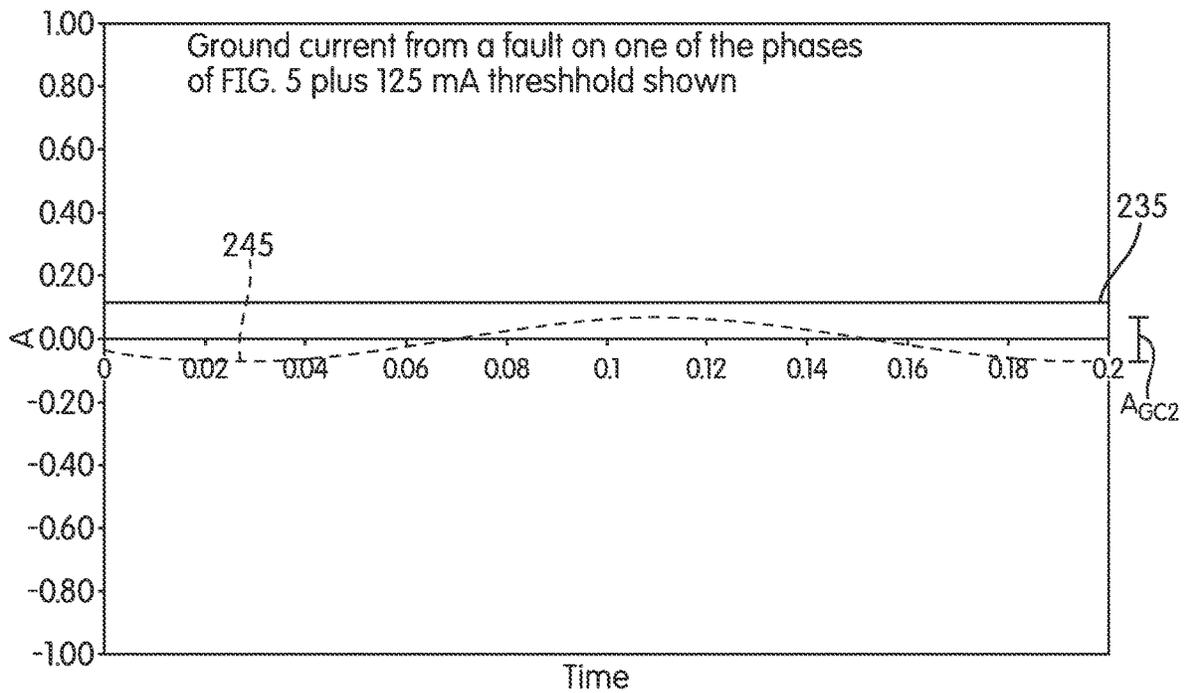


FIG. 6

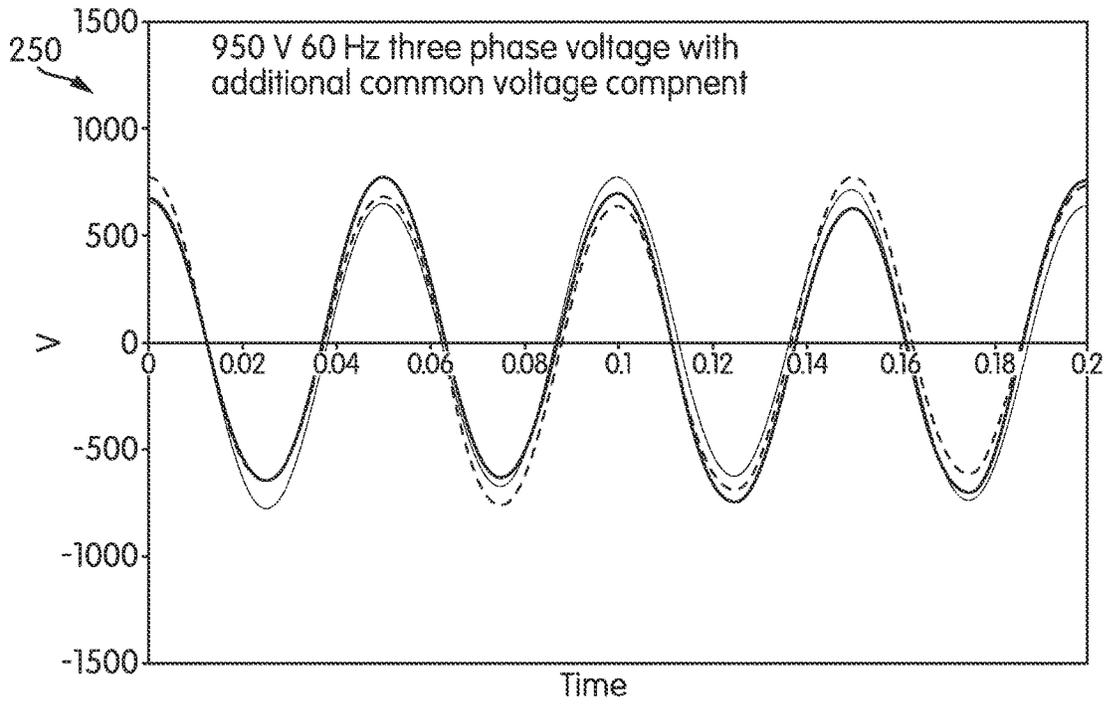


FIG. 7

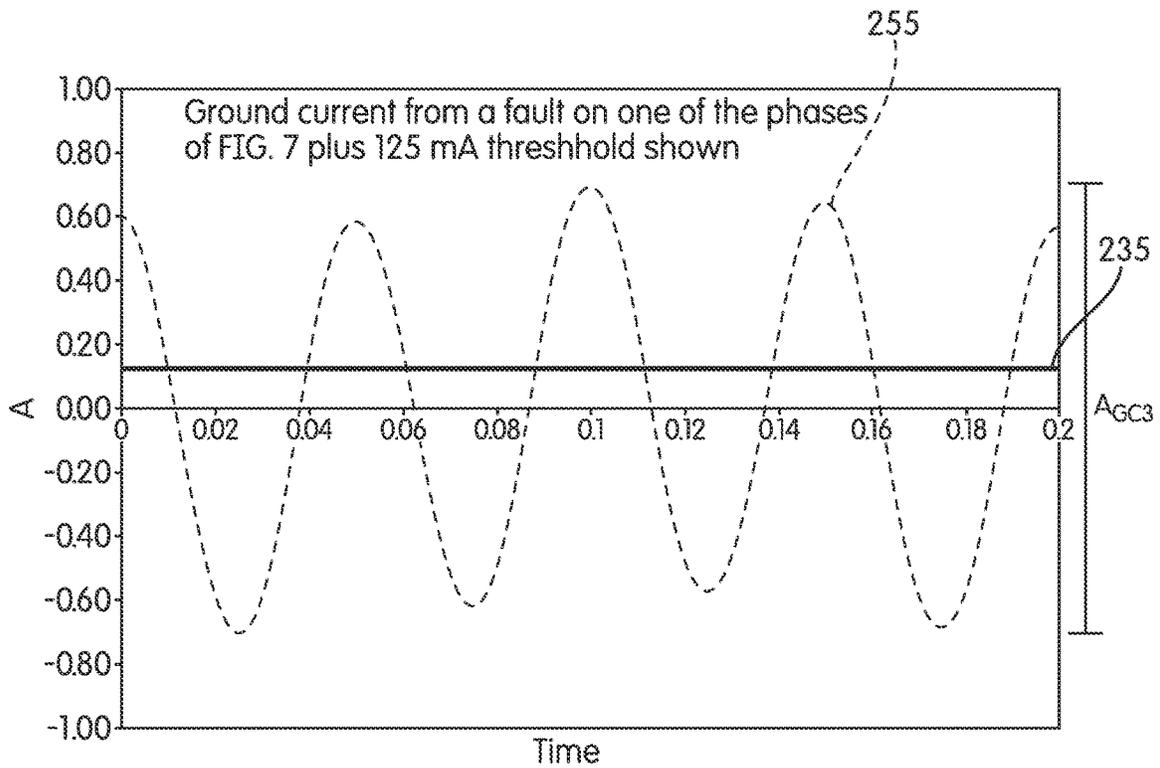


FIG. 8

1

GROUND FAULT DETECTION METHODS ON VARIABLE FREQUENCY DRIVE SYSTEMS

BACKGROUND

Embodiments of the invention relate to methods and systems for controlling drive systems, such as a variable frequency drive system used in mining equipment.

SUMMARY

Variable frequency drives (“VFDs”) allow alternating current (“AC”) motors to operate at different speeds by generating AC voltage at frequencies other than the fixed 50 Hz or 60 Hz of a utility supply. In particular, to operate a motor at a low speed, voltage of low frequency and magnitude is generated and used by the VFD to power the motor. Because the magnitude and the frequency of the voltage are reduced, current generated by any ground fault is lower than normal, which is difficult to detect using conventional fault detection methods.

Therefore, embodiments of the invention provide methods and systems for detecting ground faults at low motor speeds. In particular, embodiments of the invention add a common voltage to all power phases. The added voltage allows reliable detection of ground faults at low speeds, which may be required by the Mine Safety and Health Administration (“MSHA”) and other regulatory agencies.

In one embodiment, the invention provides a mining machine comprising a motor, an adjustable speed drive providing a voltage to the motor, the voltage having an excitation component comprising a magnitude and a frequency for operating the motor at a desired speed and including an additional voltage component for use in detecting a ground fault condition, and a ground fault relay for detecting a ground fault current when the ground fault current exceeds a predetermined threshold.

In another embodiment the invention provides a method for detecting a ground fault of a mining machine including a motor, an adjustable speed drive, and a ground fault relay. The method comprising generating, at the adjustable speed drive, a three-phase voltage for the motor, each phase of the three-phase voltage including an additional voltage signal, the additional voltage signal effecting a ground fault current; providing the three-phase voltage to the motor; detecting a ground fault current between the motor and the adjustable speed drive; and outputting an indication of a ground fault when the ground fault current exceeds a predetermined threshold.

Other aspects of the invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1a-c illustrate a mining machine according to one embodiment of the invention.

FIG. 2a schematically illustrates the mining machine of FIG. 1 connected to a remote power center.

FIG. 2b schematically illustrates a variable-frequency driver included in the mining machine of FIG. 1.

FIG. 2c schematically illustrates a ground fault relay included in the power center of FIG. 2a.

FIG. 3 is a graph illustrating a first three-phase voltage.

FIG. 4 is a graph illustrating ground current of a ground fault occurring between a phase of FIG. 3 and ground.

2

FIG. 5 is a graph illustrating a second three-phase voltage.

FIG. 6 is a graph illustrating ground current of a ground fault occurring between a phase of FIG. 5 and ground.

FIG. 7 is a graph illustrating a third three-phase voltage having an injected common signal.

FIG. 8 is a graph illustrating ground current of a ground fault occurring between a phase of FIG. 7 and ground.

DETAILED DESCRIPTION

Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein are for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having” and variations thereof herein are meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms “mounted,” “connected,” “supported,” and “coupled” and variations thereof are used broadly and encompass both direct and indirect mountings, connections, supports, and couplings.

In addition, it should be understood that embodiments of the invention may include hardware, software, and electronic components or modules that, for purposes of discussion, may be illustrated and described as if the majority of the components were implemented solely in hardware. However, one of ordinary skill in the art, and based on a reading of this detailed description, would recognize that, in at least one embodiment, the electronic based aspects of the invention may be implemented in software (e.g., stored on non-transitory computer-readable medium). As such, it should be noted that a plurality of hardware and software based devices, as well as a plurality of different structural components may be utilized to implement the invention. Furthermore, and as described in subsequent paragraphs, the specific mechanical configurations illustrated in the drawings are intended to exemplify embodiments of the invention and that other alternative mechanical configurations are possible.

FIGS. 1a-c illustrate a mining machine 100, such as a longwall shearer or a continuous miner. Although illustrated as a continuous miner, in other embodiments, the mining machine 100 is a rope shovel, a hybrid mining shovel, a dragline excavator, or other type of industrial machine or mining machine. The mining machine 100 includes a cutter system 105, which includes rotating cutters 110 with teeth 115. The teeth 115 scrape ore (e.g., coal) from a ceiling in a mine shaft. The cutter system 115 is rotationally driven by a pair of motors via a gear box. In particular, the gear box receives the rotational output of the pair of motors and uses the output to drive the cutter 110. Falling ore is gathered in a collecting tray 120 and funneled by gathering heads 125 toward a conveyor 130. The gathering heads 125 are each rotated by a separate motor. Arms 135 push ore from the collecting tray 120 onto the conveyor 130. The mining machine 100 further includes a set of left and right tracks 140 to provide movement of the machine 100. Each set of tracks is driven by a separate motor.

As illustrated in FIG. 2a, the mining machine 100 includes a variable frequency drive (“VFD”) 210 connected to a motor 205. A trailing cable 300 connects the mining

machine **100** to a remote power center **150**. The remote power center **150** includes a power source **200**, one or more ground fault relays **215** and a neutral grounding resistor (NGR) or neutral earthing resistor (NER) **227** which connects the power source **200** to earth or ground. In the example shown in FIG. **2a**, the NGR is 1100 ohms. In other embodiments, the NGR may be a different value. It should be understood that only a single motor and a single VFD is illustrated in FIG. **2a** to simplify the following explanation. The mining machine **100** can include multiple motors and multiple VFDs, and embodiments explained herein may be applied to each motor and each VFD of the mining machine **100**. In the illustrated embodiment, the power source **200** provides three-phase (A, B, C) alternating current (“AC”). In some embodiments, the power source **200** is an AC power source providing approximately 950 volts at approximately 50 Hz to approximately 60 Hz.

The motor **205** is an AC electric motor. In some embodiments, the motor **205** is a three-phase AC electric motor. In some embodiments, the motor **205** is an AC induction motor. In other embodiments the motor **205** is an AC synchronous motor.

The VFD **210** is an adjustable-frequency drive. As illustrated in FIG. **2b**, the VFD **210** can include a rectifier **210a**, a direct-current link **210b**, an inverter **210c**, and a controller **210d**. The VFD **210** operates the motor **205** at variable speeds by generating AC voltage at variable magnitudes and variable frequencies different than the AC voltage provided by the power source **200**. For example, the VFD **210** can be configured to output AC voltage having magnitudes approximately (near) 0V to approximately 900V (with respect to ground) and frequencies from approximately (near) 0 Hz to approximately 120 Hz.

The controller **210d** governs the overall operation of the VFD **210**. The controller **210d** sets the magnitude and frequency of the AC voltage outputted to the motor **205**. In some embodiments, the VFD controller **210d** includes a processor **216**, non-transitory memory **218**, and an input/output (“I/O”) interface **219**. The memory **218** stores instructions executable by the processor **216** and various inputs/outputs. The I/O interface **219** allows communication between the controller **210d** and other systems and devices, such as other components of the mining machine **100**. In some instances, the processor **216** includes one or more of a microprocessor, digital signal processor, field programmable gate array, application specific integrated circuit, or the like.

In some embodiments, the controller **210d** receives instructions from a user interface **220**. The user interface **220** can include a display, such as a liquid crystal display (“LCD”), one or more light emitting diodes (“LEDs”) or other illumination devices, a heads-up display, or a combination thereof. In some embodiments, the user interface **220** includes additional feedback devices, such as speakers for providing audible feedback and/or vibration devices for providing tactile feedback. The user interface **200** can also include one or more input devices, such as a keypad, a touchscreen, push buttons, etc., for interacting with a user. In some embodiments, the instructions received by the controller **210d** through the user interface **220** include instructions for an operating speed of the motor **205**.

The ground fault relay **215** (also referred to herein as the ground fault monitor **215**) monitors operation of the mining machine **100** to detect ground faults **217**. As illustrated in FIG. **2c**, the ground fault relay **215** includes a controller **215a** and one or more current sensors **215b**. In some embodiments, the controller **215a** includes a processor **221**,

non-transitory memory **222**, and an input/output (“I/O”) interface **223**. The memory **222** stores instructions executable by the processor **221**. The I/O interface **223** allows communication between the controller **215a** and other components of the power center **150**. The ground fault relay **215** monitors for ground faults **217** by monitoring the ground currents of each power phase provided to the motor **205**. If a ground fault **217** develops anywhere between the power source **200** and the motor **205**, the ground fault relay **215** provides an indication (e.g., to the VFD controller **210d** for subsequent output to a user-interface, or directly to the user-interface and VFD controller **210d** simultaneously). In some embodiments, the ground current of a ground fault **217** must be above a predetermined threshold to be detected by the ground fault relay **215** (i.e., the ground current must be above a predetermined threshold to be sensed by the current sensor **215b** of the ground fault relay **215**). In some embodiments, the predetermined threshold is within a range of approximately 10 mA to approximately 5 A.

In operation, the VFD **210** receives three-phase power from the power supply **200** via phases A, B, C. The VFD controller **210d** receives a motor speed via the user-interface **220**. The VFD controller **210d** sets a magnitude (with respect to ground) and frequency of an adjusted AC voltage (having three-phases U, V, W, and an excitation component) corresponding to the received motor speed. The VFD **210** provides the adjusted AC voltage to the motor **205**, via phases U, V, W, for operating the motor at the received motor speed. The motor **205** receives the three voltage phases (U, V, W) at the three motor inputs **205a**, **205b**, and **205c** and operates at the received motor speed. For example, when operating the motor **205** at a low speed, the VFD **210** provides a voltage to the motor **205** having a lower magnitude and a lower frequency than the magnitude and frequency of a voltage provided by the VFD **210** when the motor **205** is operating at a high speed. Variable-frequency drives are well-known in the art. Accordingly, additional details regarding the operation of the VFD **210** to provide adjusted power to the motor **205** are not provided herein.

While adjusted power is provided to the motor **205** by the VFD **210**, the ground fault relay **215** monitors for and detects ground faults **217**. As described in more detail below, if the ground current of a ground fault **217** is above a predetermined threshold, the ground fault relay **215** provides an indication (e.g., to the VFD controller **210d** indicating a ground fault condition).

FIG. **3** is a graph illustrating a first three-phase voltage **225** for operating the motor **205**. The first three-phase voltage **225** includes a first voltage magnitude (e.g., 950V) and a first frequency (e.g., 60 Hz). If a ground fault **217** occurs while operating the motor **205** at the first three-phase voltage **225**, the ground fault **217** produces a first ground current **230** at a first ground current magnitude, for example 500 mA (A_{GC1}), illustrated in FIG. **4**. In the example shown in FIG. **4**, the first ground current magnitude is above the predetermined threshold **235** (125 mA). In other embodiments, the predetermined threshold is higher or lower than 125 mA, as shown in FIG. **4**. The current sensor **215b** is able to sense the first ground current **230** because the first ground current magnitude is above the predetermined threshold **235**. Upon sensing the first ground current **230**, the current sensor **215b** provides a signal, or indication, to the ground fault relay controller **215a**. The ground fault relay controller **215a** then provides a signal, or indication, to the VFD controller **210d** for subsequent output to a user-interface, or directly to the user-interface and VFD controller **210d** simultaneously

5

FIG. 5 is a graph illustrating a second three-phase voltage 240 for operating the motor 205 at a low speed. The second three-phase voltage 240 has a lower voltage magnitude (e.g., 95V) at a lower frequency (e.g., 6 Hz) than the first three-phase voltage 225. If a ground fault 217 occurs while operating the motor 205 at the second three-phase voltage 240, the ground fault 217 produces a second ground current 245, as illustrated in FIG. 6. As illustrated in FIG. 6, the magnitude of the second ground current 245 is lower than the magnitude of the first ground current 230 produced with respect to the first three-phase voltage 225, and is also below the predetermined threshold 235. In this situation, the ground fault relay 215 does not provide an indication when the ground fault 217 occurs.

To correct the situation, the VFD 210 of the preferred embodiment adds a common voltage on each phase (V_{L_s} , V_{P_s} , and V_{N_s}) of the output voltage to the motor 205 (FIG. 7). The common voltage is added by the VFD controller 210a during setting of the magnitude and frequency of the adjusted voltage. Since the power to the motor 205 is conveyed by the voltage difference between the phases (V_{L_s} , V_{P_s} and V_{N_s}) of the adjusted voltage, and the same common signal is injected onto each phase, the operational speed of the motor 205 is not effected. In some embodiments, the common signal is an AC waveform, such as a low-frequency (e.g., 20 Hz) AC waveform. In other embodiments, the common signal is a pure direct current. The common signal increases the current magnitude produced by the ground current when a ground fault 217 occurs.

FIG. 7 is a graph illustrating a third three-phase voltage 250 for operating the motor 205. The third three-phase voltage 250 has a common voltage added by the VFD 210 before powering the motor 205. As illustrated in FIG. 7, the third three-phase voltage 250 includes a third voltage magnitude and a third frequency different from the magnitude and/or frequency of the first three-phase voltage and the second three-phase voltage. However, the third three-phase voltage 250 can be used to operate the motor 205 at a low speed similar to the second three-phase voltage 240. If a ground fault 217 occurs while operating the motor 205 at the modified three-phase voltage 250, the ground fault 217 produces a third ground current 255, as illustrated in FIG. 8. The current magnitude of the third ground current 255 is above the predetermined threshold 235, therefore, the ground fault relay 215 provides an indication once the ground fault 217 occurs, even though the motor 205 is being operated at a low-speed.

In some embodiments, the output voltage to the motor 205 is low-pass filtered. The common signal, however, can be a low-frequency signal. Therefore the common signal is not affected by a low-pass filter.

In some embodiments, the ground fault relay 215 is unable to detect high-frequencies. As discussed above, the common signal is a low-frequency signal. Therefore the ground fault relay 215 is able to detect ground faults 217 occurring when the motor 205 is operated by an output voltage having an injected common signal.

Thus, the invention provides, among other things, a mining machine including an adjustable speed drive for driving a motor. The adjustable speed drive allows the motor to operate at different speeds by generating AC voltage at frequencies other than the fixed 50 Hz or 60 Hz provided by a power supply. By adding an additional identical voltage component to each phase of the voltage output to the motor, ground faults are easier to detect even when the motor is operating at a low speed. In addition, because the same

6

voltage component is added to each phase, the added voltage component has no effect on the motor operation.

Various features and advantages of the invention are set forth in the following claims.

What is claimed is:

1. A mining machine comprising:
a motor; and

a ground fault relay including a ground fault relay controller and at least one current sensor; and

an adjustable speed drive including a variable frequency drive controller configured to control the adjustable speed drive to provide a voltage to the motor, the voltage having an excitation component including a magnitude and a frequency for operating the motor at a desired speed, the voltage further including an additional voltage component for use in detecting a ground fault condition, the additional voltage component modifying the ground fault current by increasing a magnitude of the ground fault current;

wherein the variable frequency drive controller receives an indication from the ground fault relay controller when the at least one current sensor detects a ground fault current that exceeds a predetermined threshold.

2. The mining machine of claim 1, wherein the additional voltage signal is one of a low-frequency alternating current waveform and a direct current.

3. The mining machine of claim 1, wherein the voltage is a three-phase voltage.

4. The mining machine of claim 1, wherein each phase of the three-phase voltage includes the additional voltage signal.

5. The mining machine of claim 1, wherein the adjustable speed drive is a variable-frequency drive.

6. The mining machine of claim 1, wherein the motor is an alternating current motor.

7. A method for detecting a ground fault of a mining machine including a motor, an adjustable speed drive, and a ground fault relay, the method comprising:

generating, at the adjustable speed drive, a three-phase voltage for the motor, each phase of the three-phase voltage including an additional voltage signal, the additional voltage signal modifying a ground fault current;

providing, by the adjustable speed drive, the three-phase voltage to the motor;

detecting, by at least one current sensor of the ground fault relay, a ground fault current between the motor and the adjustable speed drive; and

outputting, by a ground fault relay controller of the ground fault relay, an indication of a ground fault when the at least one current sensor detects a ground fault current that exceeds a predetermined threshold.

8. The method of claim 7, wherein the additional voltage signal modifies the ground fault current by increasing a magnitude of the ground fault current.

9. The method of claim 7, wherein the additional voltage signal is one of a low-frequency alternating current waveform and a direct current.

10. A system for generating variable frequency voltage for an alternating current motor, the system comprising:

a variable frequency drive including a variable frequency drive controller electrically coupled to the variable frequency drive and configured to

control the variable frequency drive to generate a

three-phase voltage for the alternating current motor;

control the variable frequency drive to generate an additional voltage signal, the additional voltage sig-

nal added onto each phase of the three-phase voltage to increase a magnitude of a ground fault current; and

control the variable frequency drive to provide the three-phase voltage injected with the additional voltage signal to the alternating current motor. 5

11. The system of claim **10**, further comprising a user interface configured to receive instructions from a user, the instructions including an operating speed for the motor.

12. The system of claim **11**, wherein the variable frequency drive controller is further configured to receive the instructions from the user interface and control the variable frequency drive to generate the three-phase voltage for the motor based on the instructions. 10

13. The system of claim **10**, further comprising a ground fault relay configured to measure the magnitude of a ground fault current with a current sensor of the ground fault relay, and output, with a ground fault relay controller, an indication of a ground fault to the variable frequency drive controller when the magnitude exceeds a predetermined value. 15 20

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